EUVL optics for Free Electron Laser sources: damage studies and the use of adjusted wavelengths

Dublin, November 8, 2017

Eric Louis, Andrey Zameshin, Andrey Yakshin, Igor Makhotkin, Igor Milov, and Fred Bijkerk

E.Louis@utwente.nl

In collaboration with the 'damage' team

Igor A. Makhotkin[a]*, Ryszard Sobierajski[b], Jaromir Chalupský[c], Kai Tiedtke[d], Gosse de Vries[e], Michael Störmer[f], Frank Scholze[g], Frank Siewert[h], Robbert W. E. van de Kruijs[a], Igor Milov[a], Eric Louis[a], Iwanna Jacyna[b], Marek Jurek[b], Dorota Klinger[b], Laurent Nittler[b], Yevgen Syryanyy[b], Libor Juha[ci], Věra Hájková[c], Vojtěch Vozda[c], Tomáš Burian[ci], Karel Saksl[cj], Bart Faatz[d], Barbara Keitel[d], Elke Plönjes[d], Siegfried Schreiber[d], Sven Toleikis[d], Rolf Loch[d], Martin Hermann[k], Sebastian Strobel[k], Han-Kwang Nienhuys[e], Grzegorz Gwalt[h], Tobias Mey[l] and Hartmut Enkisch[k]

[a]Industrial Focus Group XUV Optics, MESA+ Institute for Nanotechnology, University of Twente, Drienerlolaan 5, Enschede, 7522 NB, The Netherlands

[b] Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, Warsaw, PL-02-668, Poland

[c] Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, Prague 8, 182 21, Czech Republic

[d] Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, Hamburg, 22607, Germany

[e] ASML Netherlands B.V., P.O. Box 324, Veldhoven, 5500 AH, The Netherlands

[f] Helmholtz-Zentrum Geesthacht, Max-Planck-Strasse 1, Geesthacht, 21502, Germany

[g] Physikalisch-Technische Bundesanstalt, Abbestr. 2-12, Berlin, 10587, Germany

[h] Helmholtz Zentrum Berlin für Materialien und Energie, Albert-Einstein-Str. 15, Berlin, 12489, Germany

[i] Institute of Plasma Physics, Academy of Sciences of the Czech Republic, Za Slovankou 3, Prague 8, 182 00, Czech Republic

[j] Institute of Materials Research, Slovak Academy of Sciences, Watsonova 47, Košice, 040 01, Slovak Republic

[k] Carl Zeiss SMT GmbH, Rudolf-Eber-Strasse 2, Oberkochen, 73447, Germany

[l] Laser-Laboratorium Göttingen e.V., Hans-Adolf-Krebs-Weg 1, Göttingen, 37077, Germany

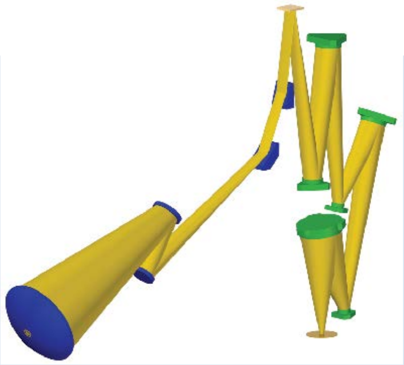
Outline

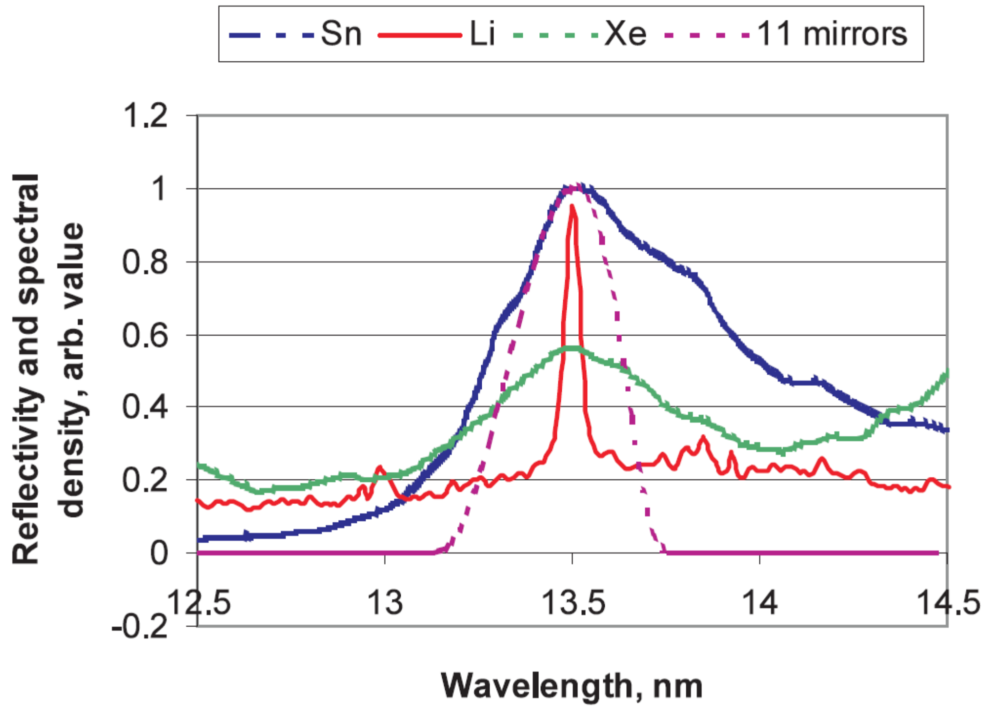
- Introduction
- Is λ=13.5 nm the best choice?
- FEL: Risk of damage to the coatings?
  - Single shot
  - Multiple shot
- Summary

EUV lithography: sources

EUV sources:

- ✓ LPP, DPP
  - can be relatively compact and cheap, but low intensity
  - to utilize all power: mirror bandwidth ≈ source bandwidth
  - choice is Mo/Si based + 13.5 nm Sn source
- ✓ FEL
  - expensive and large
  - high power, narrow band
  - tunable wavelength

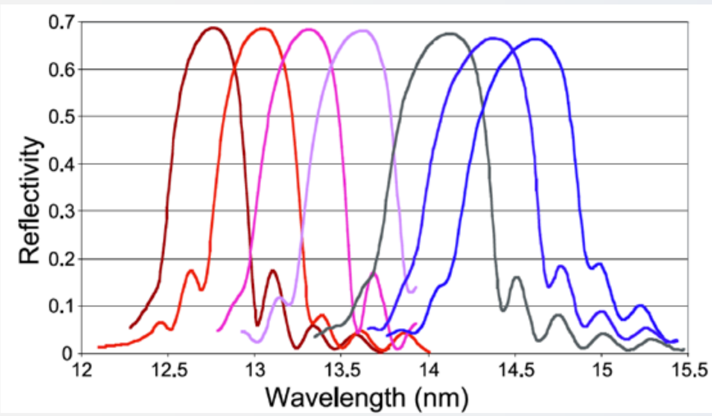


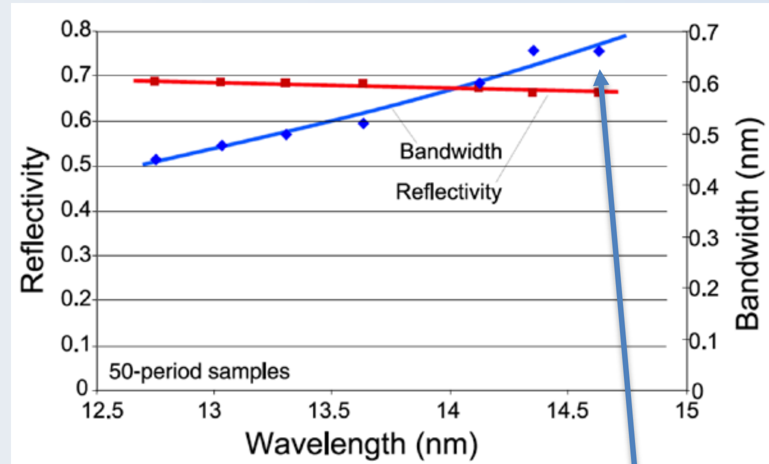


V. Banine, R. Moors, Plasma sources for EUV lithography exposure tools, J. Phys. D. Appl. Phys. 37 (2004) 3207–3212.

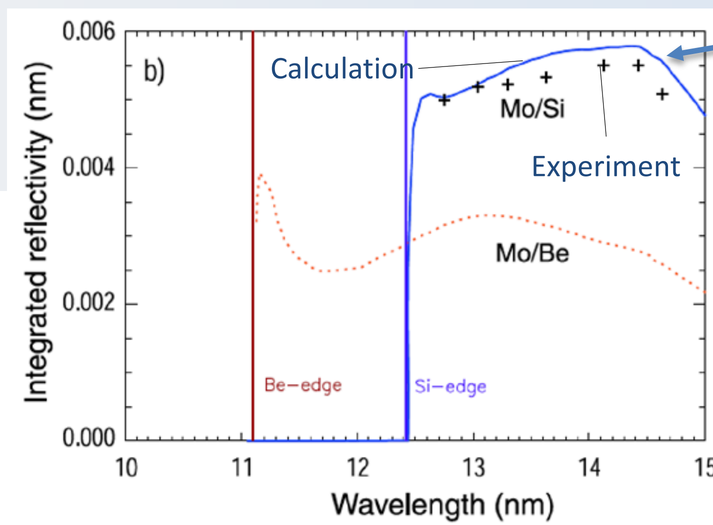
Scaling around 13.5 nm

Trade-off peak reflectivity - BW





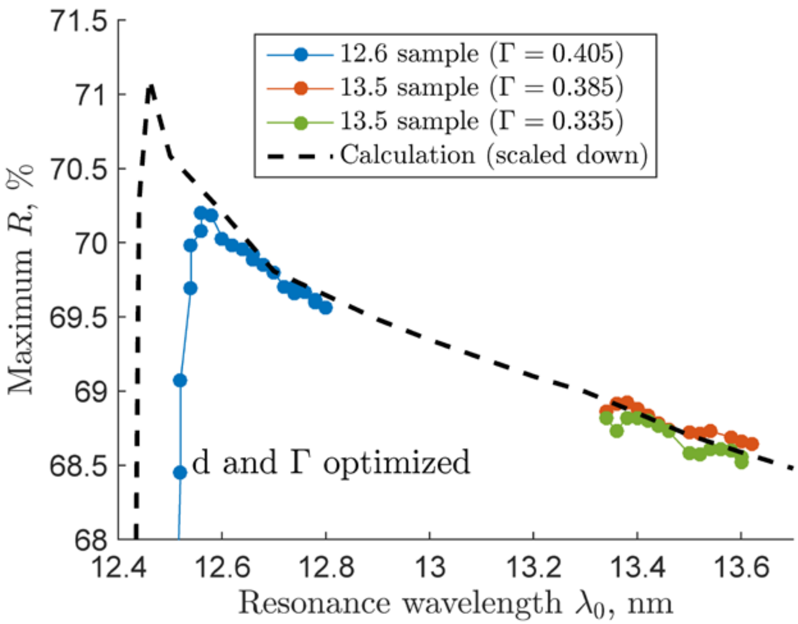
Small R-gain towards Si-L edge

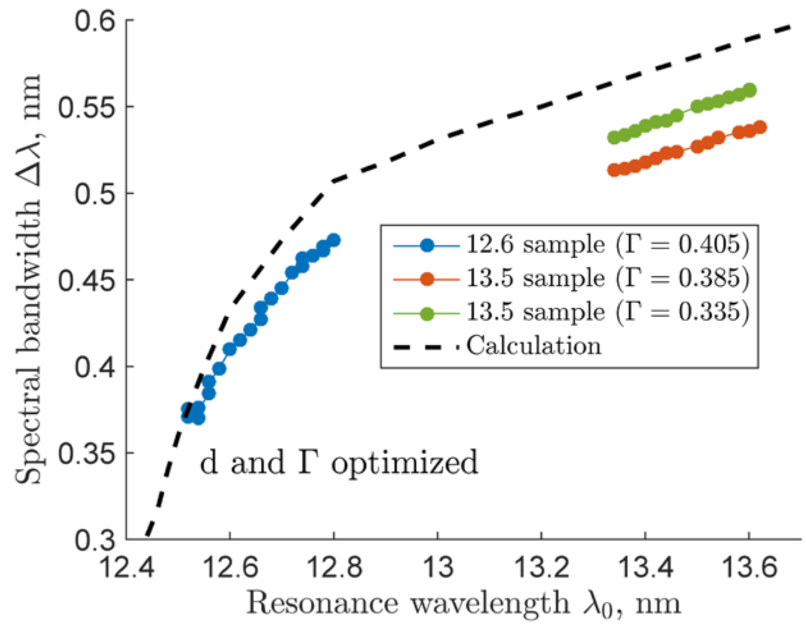


Broadband sources favour 14.4 nm

R. Stuik, E. Louis, A.E. Yakshin, P.C. Gorts, E.L.G. Maas, F. Bijkerk, D. Schmitz, F. Scholze, G. Ulm, and M. Haidl, Journal of Vacuum Science Technology B 17 (6), 2998-3002 (1999)

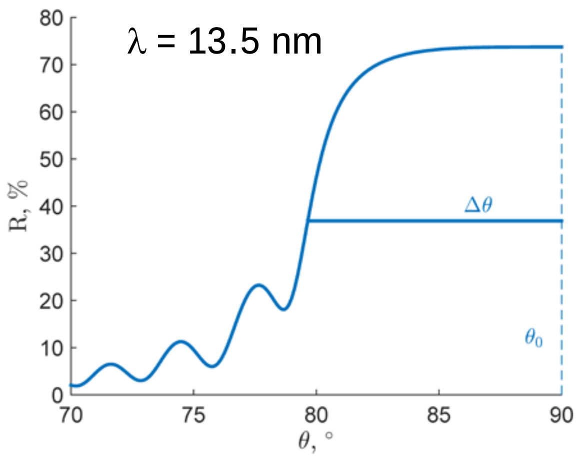
Mo/Si reflectance and bandwidth





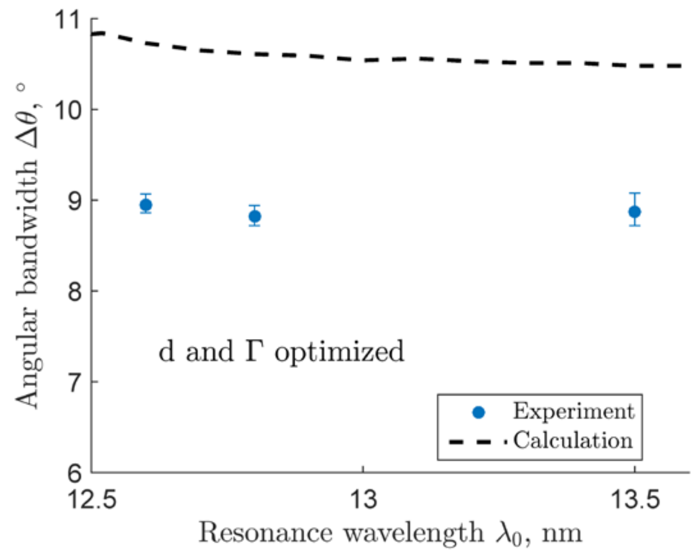
- *Shift λ towards Si $L_{2,3}$ edge: strong increase of reflectance*
  → 20-25% higher transmission of scanner optics and reduced absorption
- *Spectral bandwidth reduces, no issue for narrow band source (like FEL)*
- *Discrepancy Si $L_{2,3}$ edge experimentally and predicted by CXRO optical constants*

Angular bandwidth



$$2d\sin\theta_0 = m\lambda_0 \Rightarrow \Delta\theta = 2\sqrt{\frac{\Delta\lambda}{\lambda_0}}$$

→ Reduction angular BW expected



But... taking optical constants into account

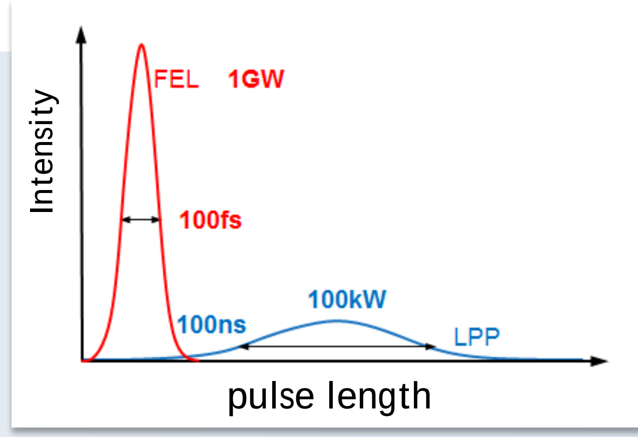
For an FEL source: shift λ towards Si $L_{2,3}$ edge: λ =12.6 nm

→ Reflection enhancement and no reduction of angular BW

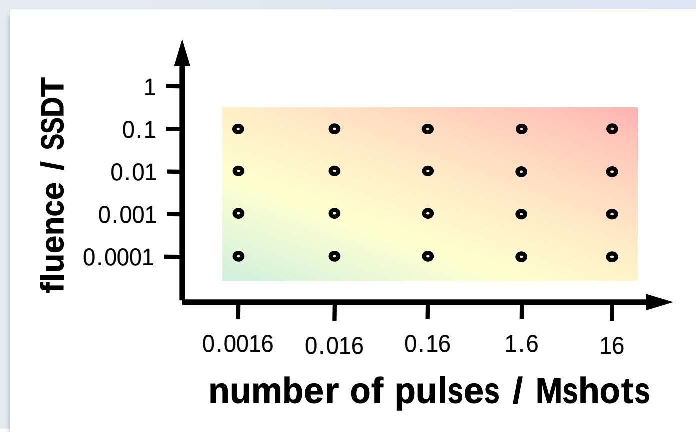
A. Zameshin et al, accepted for publ. J. of Nanoscience and Nanotechnology

Can optics withstand FEL radiation?

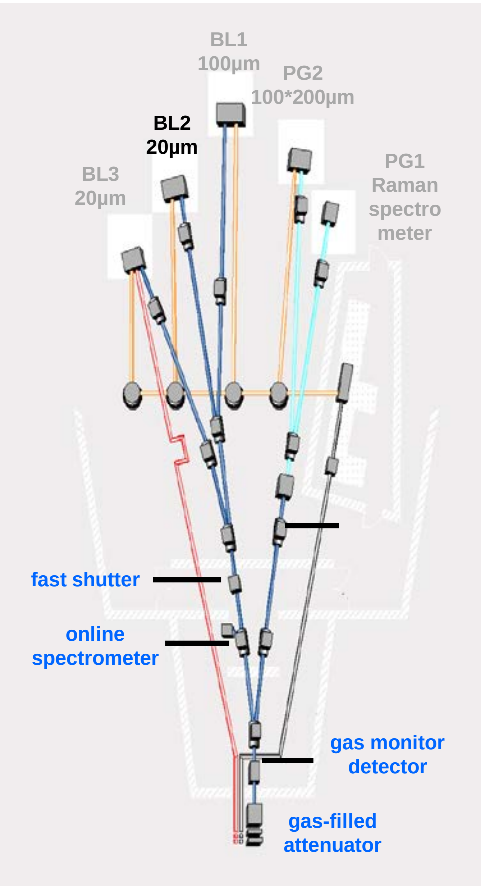
- ✓ Laser Plasma → Free Electron Laser:
  - Pulse duration 50 ns →100 fs
  - Energy per pulse 10x reduced
- ✓ 10^5 increase of peak power density

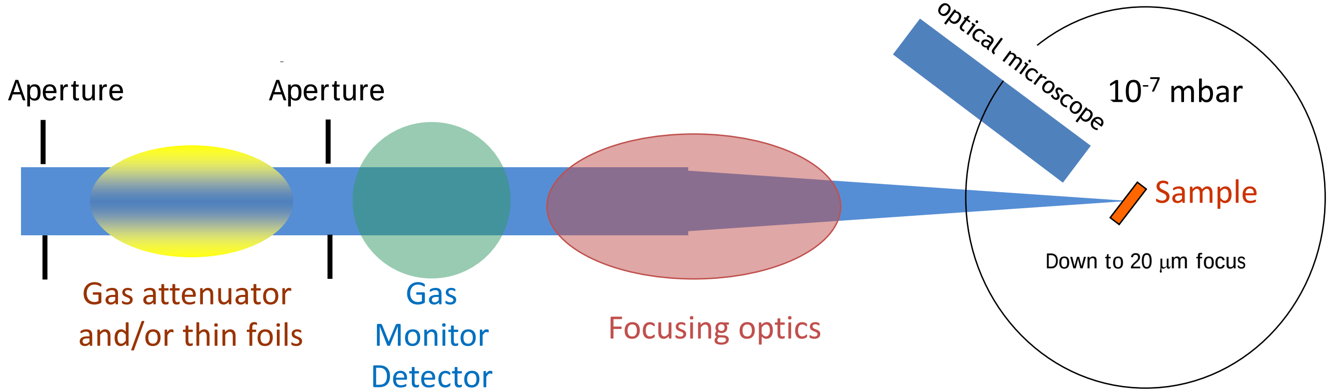


- ✓ Relevant coating materials:
  - 50 nm Ru for grazing incidence
  - 50 bi-layer Mo/Si based multilayer for normal incidence
- ✓ Twofold approach:
  - Find single shot damage threshold and damage mechanism
  - Investigate multiple shot effects at realistic fluence levels



Test set-up at FLASH (Hamburg)





FEL pulse:

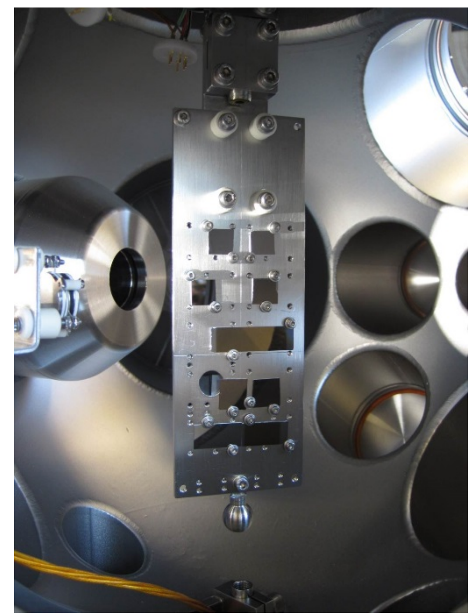
t_p = 100 fs

λ = 13.5 nm

Beam affective area - 41 μm^2

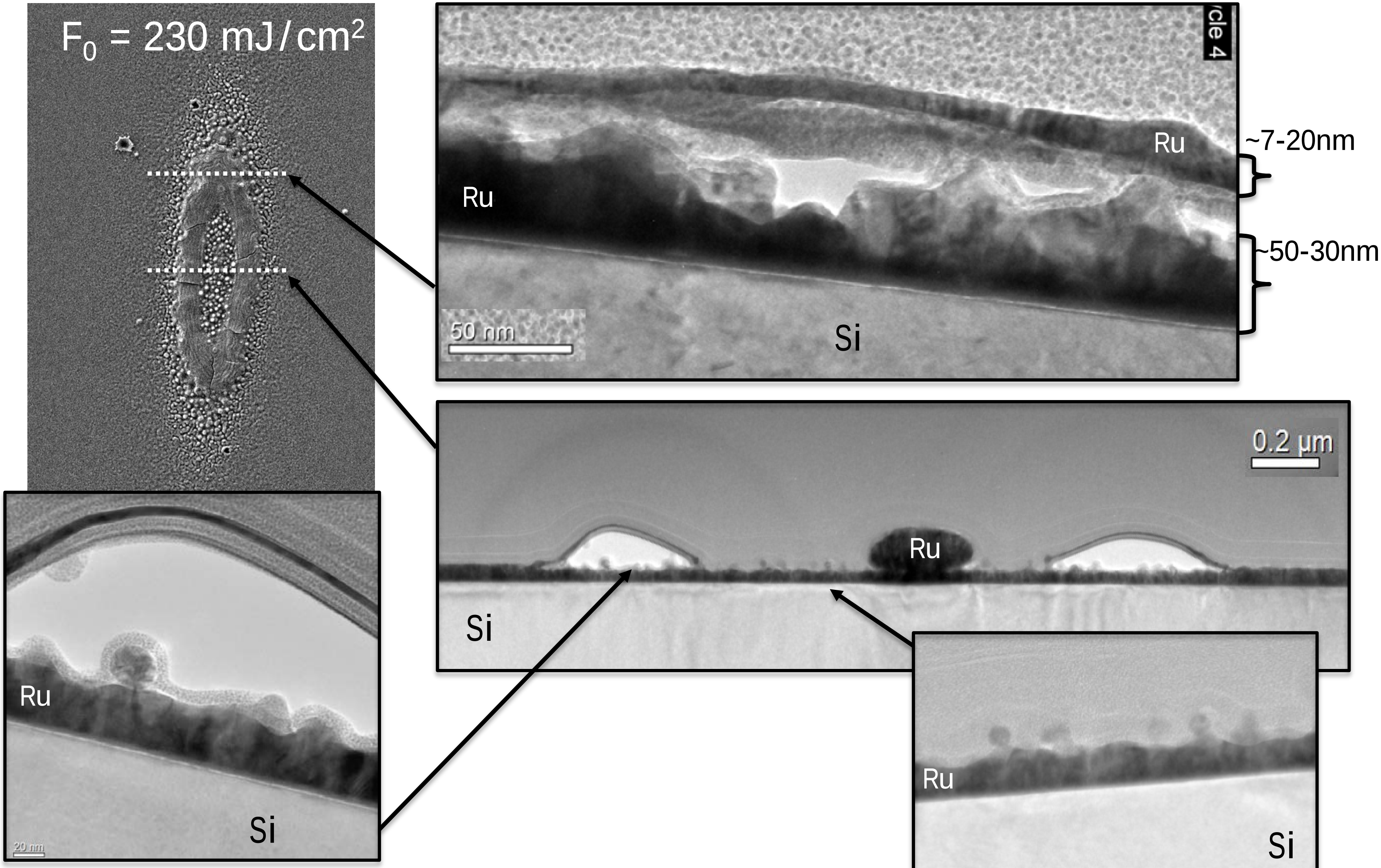
Pulse energy ~0.08 – 0.17 μJ

F_0 up to 425 mJ/cm^2

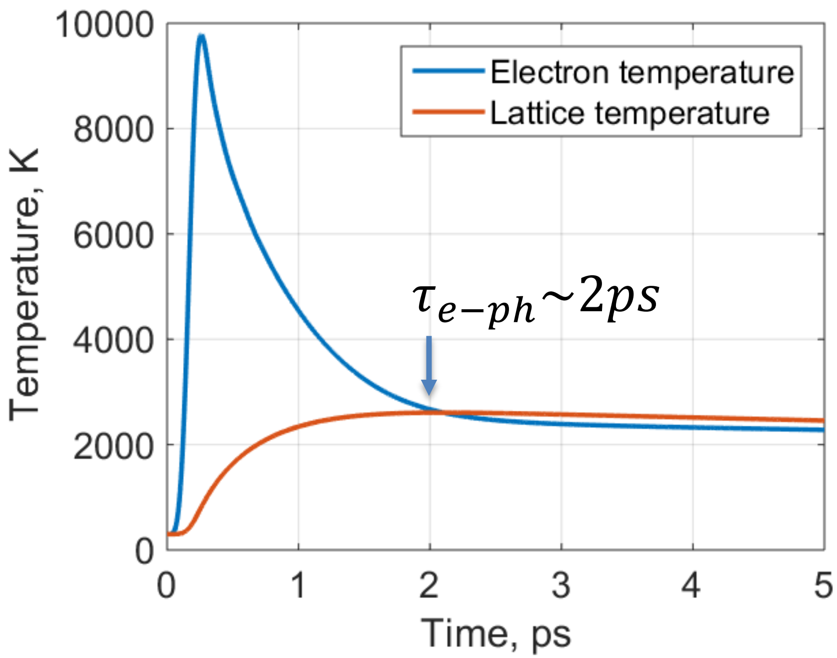


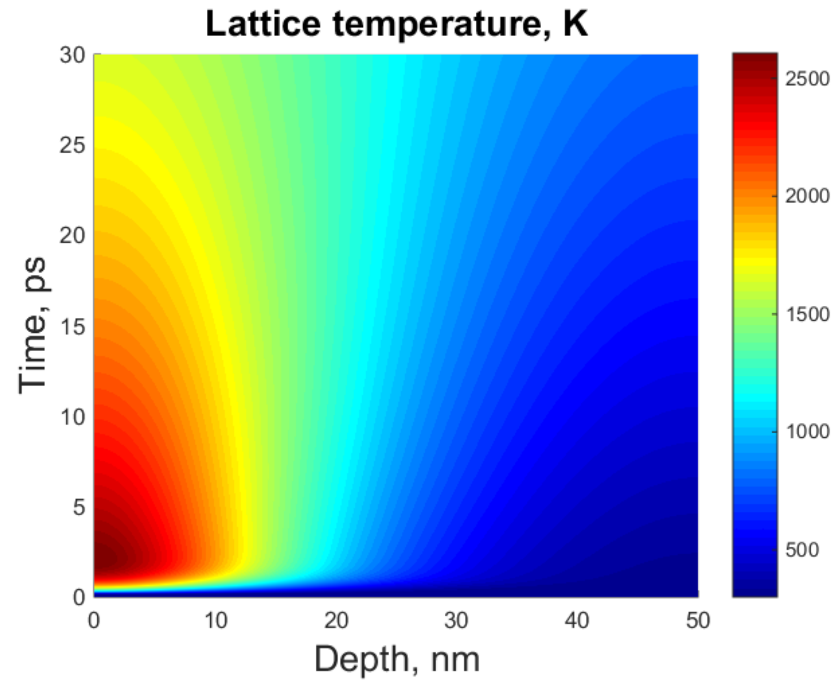
XUV MESA+ UNIVERSITY OF TWENTE. provincie Overijssel NWO ASML ZEISS PANalytical FZU HZB Helmholtz Zentrum Berlin DESY

Single shot damage of Ru: spallation of the top layer



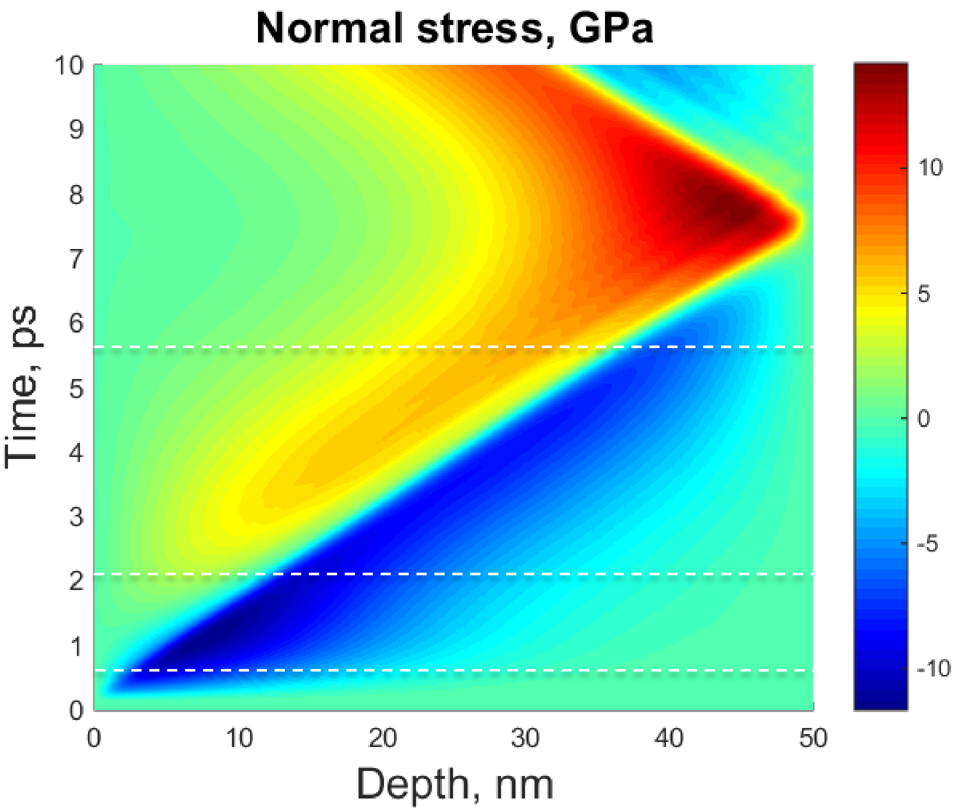
Surface temperatures of Ru , F = 51 mJ/cm²



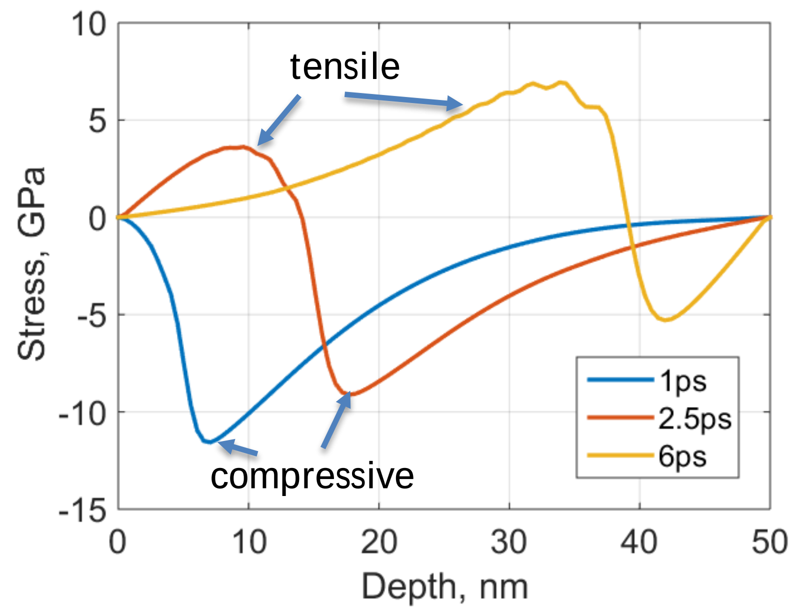


- Ru has high electron-phonon coupling factor:
  - thermal equilibrium reached in ~2 ps
  - most heat stays in top 22nm
- 2 ps to short for system to mechanically react

Stress distribution in Ru film

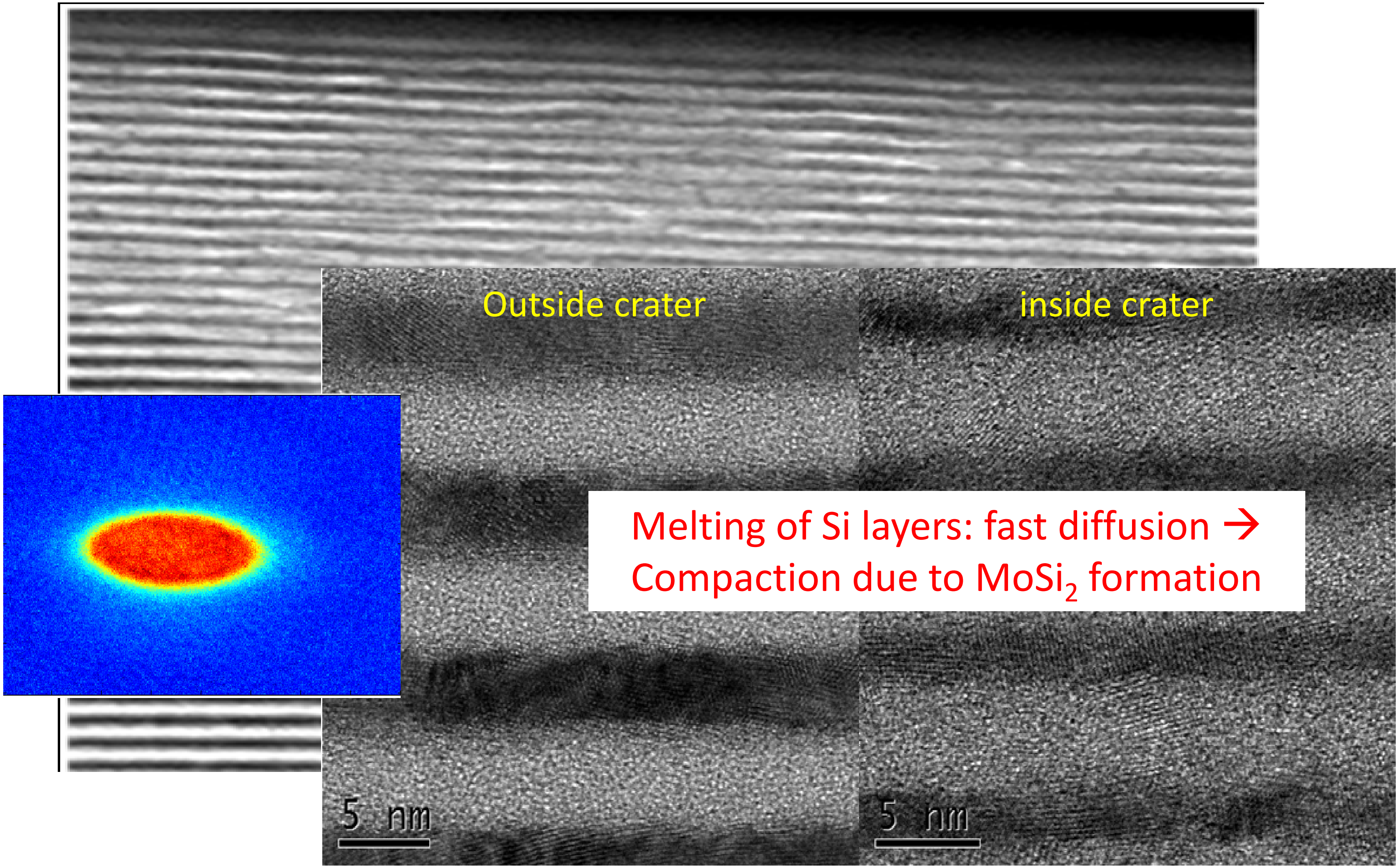


$$\rho \frac{\partial^2 u}{\partial t^2} = (\lambda + 2\mu)\frac{\partial^2 u}{\partial x^2} - (3\lambda + 2\mu)\alpha \frac{\partial T_p}{\partial x}$$



- Shock wave propagates into the layer
- High tensile stresses in depth of Ru → spallation top layer

Single shot: Atomic diffusion in Mo/Si (λ=13.5 nm)



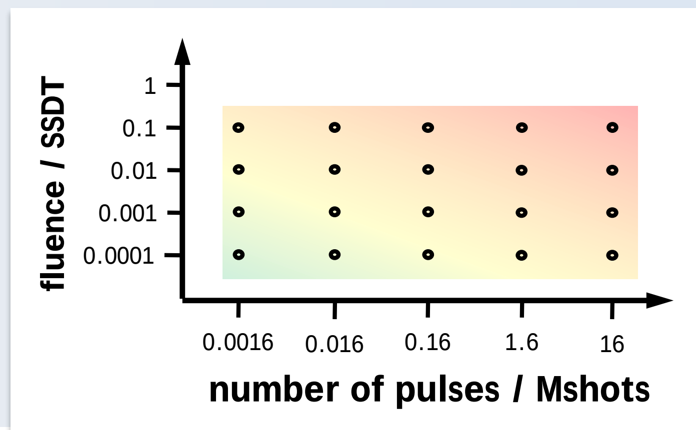
S. Khorsand et al. Optics Express, 18 (2010) 700-712; Sobierajski: 2014 Source Workshop, Dublin

Multiple pulse exposures

- ✓ Laser Plasma → Free Electron Laser:
  - Pulse duration 50 ns →100 fs
  - Energy per pulse 10x reduced
- ✓ 10^5 increase of peak power density

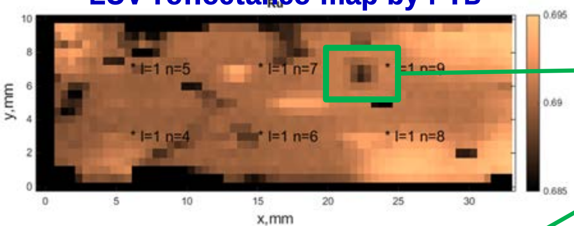
- ✓ Relevant coating materials:
  - Ru for grazing incidence
  - Mo/Si based multilayer for normal incidence

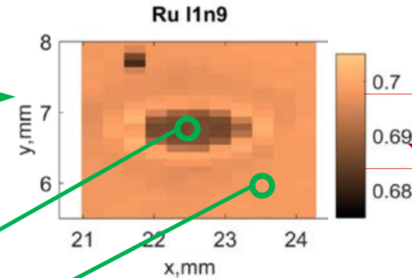
- ✓ Twofold approach:
  - Find single shot damage threshold and damage mechanism
  - Investigate multiple shot effects at realistic fluence levels



Multiple pulse exposure of Ru

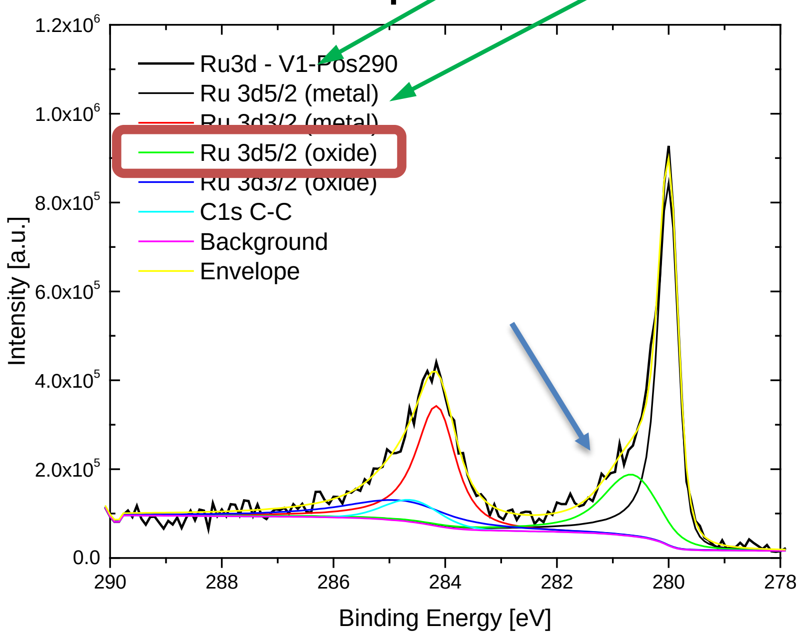
EUV reflectance map by PTB

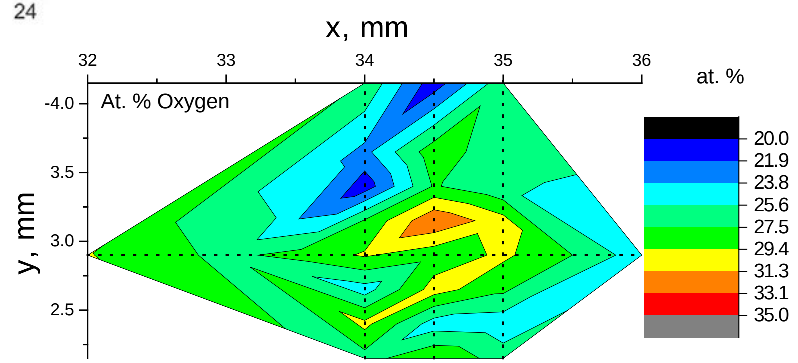




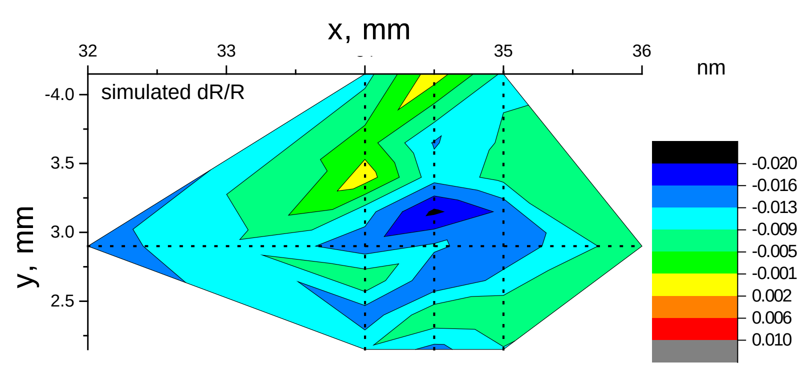
→ 1% reflectance loss after 16 Mshot @ fluence 10 % SSDT

XPS spectra





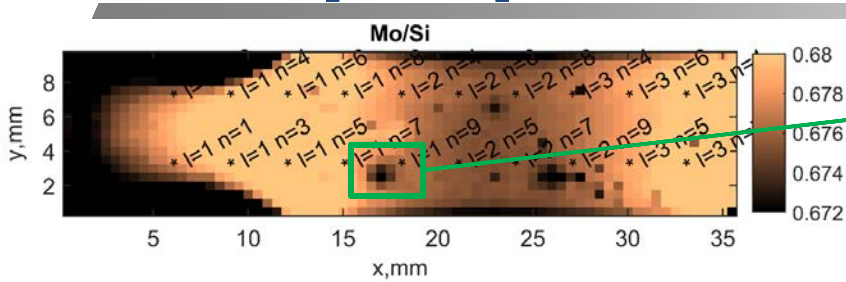
up to 15% comming from Ru-O

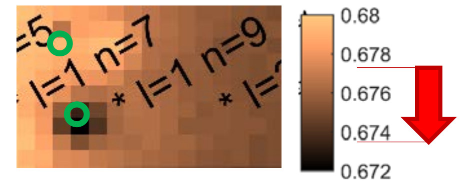


→ Reflectance loss explained by surface oxidation

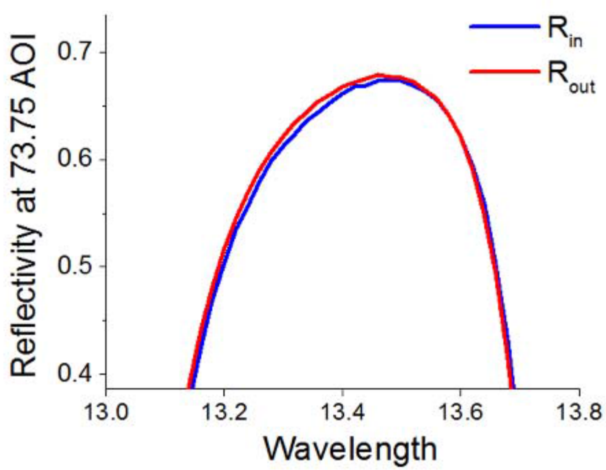
I. Makhotkin et al, subm. Journal of Synchrotron Radiation

Multiple pulse exposure of Mo/Si ML

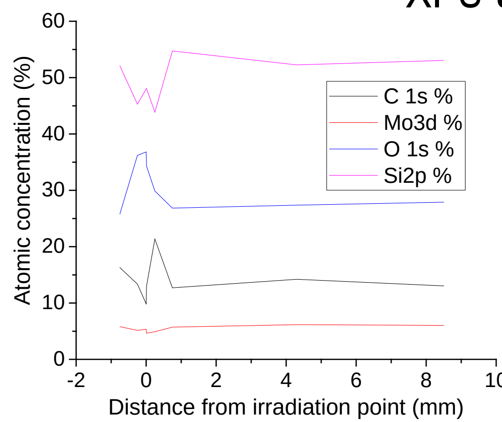


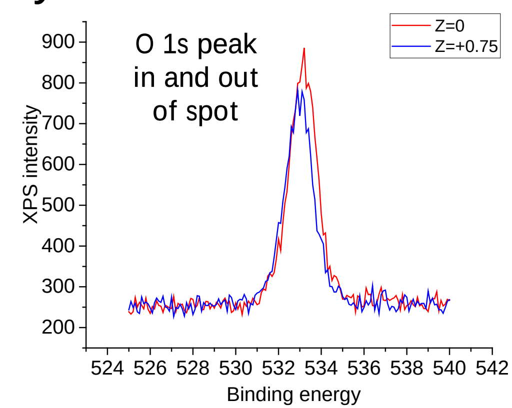


→ **0.6 % reflectance loss after 16 Mshot @ fluence 10 % SSDT**



XPS analysis





- ✓ No change of ML periodicity → no indication for in depth multilayer damage
- ✓ Top surface oxidation explains reflectance loss

Summary

- Shift of operational λ towards Si $L_{2,3}$ edge → λ = 12.6 nm
  - higher R and less absorption for Mo/Si based ML's
  - No reduction angular bandwidth
  - 20-25 % higher transmission in a scanner (for a narrow band source)
- Single shot exposure @ damage threshold
  - Ru single layer, melting of Ru → shockwave → spallation top layer
  - Mo/Si multilayer: melting of Si → enhanced diffusion and $MoSi_2$ formation
- Multiple shot exposures 16 MShot @ 10% of SSDT
  - Ru single layer, top surface oxidation and C-formation observed, explaining reflectance loss
  - Mo/Si multilayer: no in depth changes of ML observed
top surface oxidation explains reflectance loss
- No damage of Ru and Mo/Si observed for 16 MShot @ 10% SSDT level

Thanks to …

- *Team of the XUV optics group of the University of Twente*
- *Damage consortium*
- *PTB Berlin for reflectance measurements*

Thank you!